The QVLBI Doppler Demonstration Conducted With Mariner 10

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The Mariner 10 differenced doppler (QVLBI) demonstration conclusively showed that this new data type can reduce the effects of moderate unmodeled spacecraft accelerations (10^{-10} km/s²) by an order of magnitude and reduce the effects of the solar corona by a factor of five. The differenced data solutions were also very useful in making real-time navigation decisions for use by the Mariner 10 project.

I. Introduction

Two of the primary error sources that limit interplanetary navigational capabilities are unmodeled spacecraft accelerations and charged particles in the solar corona and space plasma. Small unmodeled accelerations that may only perturb the trajectory by 10 km over a one-month time span can degrade the data sufficiently to produce a 1,000-km error in the estimate of the position of the spacecraft. The influence of the space plasma upon navigational accuracies is difficult to predict because of its random nature. However, space plasma events have been observed in the radio metric data that could cause 1,000-km navigational errors. The solar corona is often the dominant error source when the Sun-Earth-spacecraft angle is less than 10 deg and may produce navigational errors as large as several thousand kilometers.

Analysis and simulations (Refs. 1 and 2) have shown that the navigation of spacecraft subject to these error sources can be greatly enhanced by simultaneously obtaining doppler data from two widely separated stations. However, before this new simultaneous doppler data type, sometimes called Doppler Quasi Very Long Baseline Interferometry (DOPPLER QVLBI), can be incorporated into a mission design, it is necessary to obtain flight data and demonstrate that the expected improvement in navigational capabilities can actually be achieved.

The first attempt at demonstrating the advantages of simultaneous doppler data was made in 1971 with Mariner 9 two-way and three-way data taken from Deep Space Stations (DSSs) 12 and 41 during the month and a half prior to Mars encounter. The results (Ref. 3) though promising, are not conclusive because there was only a limited amount of data and inadequate knowledge about the behavior of the frequency system.

In 1973 it was decided to conduct the general simultaneous doppler demonstrations in the five basic phases described in Table 1.

The short baseline experiments mentioned in Table 1 are necessary to determine the quantities that describe the characteristics of the frequency system. These numbers can then be incorporated into accuracy analysis studies to determine the quality of the simultaneous doppler data. The first short baseline experiment was conducted during the summer of 1973 using Pioneer 10 and 11 data. Results (Refs. 4 and 5) indicate that the frequency offsets between stations using Rb standards vary slowly and linearly with a long term (2×10^6 s) stability on the order of 2 parts in 10^{12} ($\Delta f/f$). Accuracy analysis studies (Ref. 6) predict that the corresponding simultaneous doppler data should be capable of reducing the effects of moderate ($10^{-10} \rightarrow 10^{-11}$ km/s^2) unmodeled accelerations by an order of magnitude.

The purpose of phase 2 of the simultaneous doppler demonstration was to show that the underlying principles of the differencing technique are sound. This was accomplished during the Pioneer 10 encounter by showing that the orbit determination (OD) solution based upon differenced two-way and three-way doppler data was two or three orders of magnitude better than the corresponding solutions based upon only the conventional two-way data when the spacecraft was subject to large (10^{-8} km/s^2) unmodeled accelerations produced by the Jovian satellites. The detailed results of this demonstration are described in Ref. 7.

Mariner 10 provided an excellent opportunity for showing that simultaneous doppler data based upon Rb oscillators are capable of reducing the sensitivity of the orbit determination solution to moderate unmodeled accelerations ($10^{-10} \rightarrow 10^{-11}$ km/s^2) by an order of magnitude. The first nine-month period of the Mariner 10 simultaneous doppler demonstration is the primary subject of this article and is described in some detail in later sections. The demonstration was successful and generally gave the expected results although there were some surprises.

To provide simultaneous doppler data which, when differenced, are capable of substantially reducing problems produced by small (10^{-12} km/s^2) unmodeled accelerations typical of Mariner-type spacecraft will probably require hydrogen masers and possibly dual frequency data. A short baseline experiment to determine the quality of H-maser doppler data may be able to be performed in 1975. It is anticipated that a definitive simultaneous doppler demonstration using H-masers and dual frequency data will take place during Viking if the necessary data are taken.

II. Strategy

The best demonstration of the navigational advantages of a new data type is obtained from comparisons of orbit determination estimates of a spacecraft trajectory based upon the new data types, and based upon conventional data types with the actual trajectory. Currently, the only means of determining the actual (to within a few kilometers) trajectory of a spacecraft is to use both pre- and postplanetary encounter data. Unfortunately, for orbit determination, two weeks before both the Venus and the first Mercury encounters there were maneuvers. The uncertainty in these maneuvers is large enough so that even though the encounter data are extremely powerful, they are useless in determining the premaneuver trajectory with an accuracy better than approximately 100 km. Therefore, the desired precise comparison of trajectory estimates based upon the new data type and the conventional data type with the actual trajectory will be available only for two-week data arcs preceding Venus and Mercury encounters. Restricting the study to these short arcs immediately preceding encounter has two major deficiencies. First, since the data are so close to encounter, the orbit determination solution is primarily a spacecraft position determination. Errors in the velocity terms, because of the long mapping time, could be of primary importance. If the data were taken far away from encounter, errors would not be immediately visible in solutions based upon data taken just before encounter. This limiation is particularly important in a demonstration involving simultaneous doppler data from which the position of the spacecraft is relatively better determined than its velocity. The second deficiency resulting from restricting the study to data taken two weeks before Venus and Mercury would not permit analysis of long data arcs. Since the influence of error sources is often quite different if the solution is based upon long data arcs as opposed to short data arcs, an analysis of long data arcs is very valuable. Following sections will discuss the results of orbit determination solutions based upon five data arcs. The time and length of these two short and three long arcs are illustrated in Fig. 1. Also included in Fig. 1 are some of the events, which occurred during the Mariner 10 mission, that were particularly important to navigation. As discussed above, the short arcs of data are particularly important because a comparison can be made between the solutions based upon simultaneous doppler and solutions based upon conventional data with the actual trajectory, which is known to an accuracy of a few kilometers. The actual trajectory of the spacecraft during the time period of the long arcs is uncertain to 50–500 km and therefore definitive demonstrations using long arc data cannot be accomplished. However, because of the importance of investigating the value of the data taken during these long arcs we will include the results of the analysis of these data.

In trying to determine the orbit of a spacecraft from a particular arc of radio metric data, the normal procedure is to make many solutions using different combinations of data types (e.g.; doppler-only, doppler plus range), different parameters in the estimate list [e.g., state (position and velocity of the spacecraft) only, state plus station locations], and different amounts of data. This procedure was followed in both the real-time and postencounter orbit determination portion of the simultaneous doppler demonstration. For the sake of brevity and clarity, only a small representative fraction of the many results will be shown in latter sections. Unless otherwise indicated, the orbit determination solutions that will be shown will be based upon doppler and range data where either the state only, or state and station locations were estimated. A frequency bias and drift for each station may also be estimated when three-way doppler data are used. The usual a priori information on the estimated parameters and data weights on the range, two-way doppler, and differenced doppler are shown in Table 2. The data weights are not primarily picked to represent the real quality of the various data types. Rather, they are chosen to establish a relative strength of the data types. In a solution employing differenced doppler data, the conventional data are deweighted so that they are used only to provide geocentric range and range-rate information, and will not influence the declination and right ascension estimates that are sensitive to unmodeled accelerations.

III. Quality of Three-Way Doppler Data

The simultaneous doppler data used in this demonstration were obtained by using conventional two-way and three-way doppler data. As mentioned earlier, the three-way data contain a temporal bias that may severely limit their effectiveness.[1] Because of the importance of establishing the quality of the three-way data, it will be worthwhile to pause and take a general look at this problem before proceeding into a discussion of the orbit determination solutions. The more information that can be obtained relating to the behavior of these biases will allow the development of more effective techniques to reduce their degrading influence on navigational capabilities. For example, if the three-way biases were constant for each station, their effect on navigation could be almost entirely eliminated by simply estimating constant biases in the orbit determination process.

As mentioned earlier, the best means of determining the quality of the three-way data was by conducting short baseline experiments. This was first done in the summer of 1973 with the Pioneer 10 and 11 spacecraft and showed that the biases between DSSs 12 and 14 were typically about 10 mHz and fairly constant over a ten-day interval, but had a noticeable drift of about 1 mHz/week over a 60-day interval. Because of its importance this short baseline experiment was repeated a number of times during Mariner 10. Figure 2 shows the average difference of one minute two-way and three-way data on the indicated days between DSSs 12 and 14. The standard deviation about this average was less than 5 mHz. Since station location and transmission media errors will produce less than a 0.5-mHz error (Ref. 4) almost all of the 10–20 mHz difference can be attributed to differences in the frequency systems at DSSs 12 and 14. Also included in Fig. 2 is the 6-mHz difference in the two-way and three-way data taken from Pioneer on March 26, 1973. From Fig. 2 it is apparent that these differences between the two-way and three-way data on 80% of the passes may grossly be described by a combination of a constant bias and a linear drift with time. The remaining three passes on January 25 and 28 and March 18 deviated considerably from such a model for reasons that are currently unexplained.

Accuracy analysis studies based upon the results of the short baseline experiments indicate that for orbit determination solutions based upon differenced doppler data, a constant frequency bias should always be included in the list of estimated parameters and a linear drift term should also be estimated for data arcs longer than two weeks. Figure 3 contains the estimate of the biases and drift terms from data taken during four data arcs. This figure shows that the drift terms estimated in the long arc solutions tend to connect the frequency biases computed within each data arc. However, it is also readily apparent that the current bias and linear drift model does not represent reality as closely as one would like.

IV. Pretrajectory Correction Maneuver 2 (TCM 2) Solutions

The first differenced doppler solutions were made using data starting 30 days prior to the second trajectory correction maneuver (TCM 2) and continuing until a few

[1] The three-way biases problem can probably be eliminated by obtaining Simultaneous Interference Tracking Technique (SITT) data. This extremely clever technique was developed by G. Wood of JPL.

days before the maneuver. Unfortunately, as shown in Fig. 4, the simultaneous doppler data were very sparse and consisted mainly of passes less than one hour in length. Representative aim plane solutions for both the conventional and the differenced data solutions are shown in Fig. 5. Also included in Fig. 5 is the current best estimate (CBE) of the actual trajectory based upon encounter data. The accompanying uncertainty is fairly large (100 km) because of uncertainties in the magnitude and direction of TCM 2.

During this time span the spacecraft was subjected only briefly to unmodeled accelerations that were larger than the 3×10^{-12} km/s^2 Mariner 10 specifications. Since the difference data solutions can be expected to be superior only when there are unmodeled spacecraft accelerations or some other common error source affecting the data, it is not surprising that the conventional solutions based upon almost continuous data will be generally better than the differenced data solutions. Indeed, it is surprising that the difference data solutions are so good since there was so little data.

One of the interesting features of Fig. 5 is that the conventional data solutions are highly correlated, all having nearly the same value for **B•T**, while the differenced data solutions are more independent. The position of the spacecraft in the ecliptic (i.e., the **B•T** direction) is generally much better determined than the direction out of the ecliptic (i.e., **B•R**) from conventional data, because most of the geocentric acceleration occurs in the ecliptic and this acceleration will be a strong source of **B•T** information. In the differencing process most of the acceleration information is removed so that the differenced doppler solutions will not in general determine **B•T** significantly better than **B•R**.

V. TCM 2 to Venus Encounter

On January 28, 1974, seven days before Venus encounter, Mariner 10 experienced a large gas leak of 80-min duration at the conclusion of a gyro test. This leak gave the spacecraft a 1.8×10^{-9} km/s^2 acceleration in the Earth direction, and it was speculated at the time that it could possibly move the encounter trajectory by over 100 km. Since a 100-km miss at Venus would have severely limited the science return at Mercury, all possible efforts were made to quickly reestablish the orbit of the spacecraft so that another pre-Venus maneuver could be made if necessary. Processing the conventional two-way doppler data and completely ignoring the gas leak gave errors in the estimate of the encounter trajectory of over 700 km. Much better results were obtained by treating the gas leak as a motor burn that was included in the list of estimated parameters. Figure 6 shows that the solutions obtained in this way agreed with the current best estimate (using pre- and postencounter data) in the aim plane to within 50 km.

Fortunately, for a few days following TCM 2, a relatively large amount of three-way data was taken. Using these data along with the extensive three-way data coverage following the gas leak provided enough information to give viable simultaneous differenced doppler solutions. Since the differenced doppler solutions should be insensitive to unmodeled accelerations such as large gas leaks, it was not necessary to model the gas leaks as a solve-for instantaneous maneuver. As shown in Fig. 6, the real-time differenced doppler solutions agreed with the current best estimate of the aim plane parameters to within 30 km and were generally as accurate as the better conventional data batch and sequential filter solutions. Having a real-time differenced doppler solution during this most critical navigation period was extremely valuable and provided a great deal of confidence that an additional pre-Venus maneuver was not necessary. In principle, the differenced data should be superior to the batch solution where the leak is modeled as a maneuver, since estimating a maneuver essentially breaks the arc in two. The differenced data solution should also be better than the usual sequential filter solution since it requires no modeling of the accelerations.

As has just been shown, the simultaneous doppler data can be extremely useful in reducing the problem caused by large ($> 10^{-10}$ km/s^2) unmodeled accelerations of short duration, such as the January 28 episode on Mariner 10 and the Encounter-7 day "happening" of Mariner 7. It is much more common for the unmodeled spacecraft accelerations to be smaller in magnitude and to continue for many days. As mentioned in the introduction, preflight accuracy analysis studies indicated that for systems based on a rubidium oscillator, the differenced doppler orbit determination solution will be superior to the conventional solution when the spacecraft is subject to continuous moderate unmodeled accelerations on the order of $10^{-10} \rightarrow 10^{-11}$ km/s^2. Although the Mariner did not experience any such unmodeled acceleration of this size except for very brief times, it was easy to generate a continuous unmodeled acceleration of 10^{-10} km/s^2 by simply not modeling the solar pressure. When the solar pressure model is turned off, the before-the-fit two-way doppler residuals gradually increase from a few millihertz at the epoch, 13 days before encounter (E−13), to 1.7 Hz one day before encounter. As shown in Fig. 7 the orbit determination solution based upon the conventional data for the spacecraft experiencing such an unmodeled acceleration is in error by 400 km.

Turning off the solar pressure model should produce virtually no change in the before-the-fit residuals of the differenced doppler data, since this data type should be insensitive to unmodeled accelerations. The real data confirmed this expectation because the before-the-fit differenced doppler residuals based upon nominal trajectories with the solar pressure turned on and off both gave residuals of a few millihertz. The aim plane solutions using the differenced doppler data with the solar pressure model turned off are almost as good as the solutions with the solar pressure model turned on. As shown in Fig. 7, the difference between the predicted aim plane coordinates and the actual values are 45 km at E-5 days and 17 km at E-1 day. Thus, there is more than an order of magnitude improvement in the aim plane solution in using the differenced data rather than the conventional data. This is an extremely important result. Not only does it demonstrate the superiority of the differenced data in dealing with unmodeled accelerations, but it also indicates that our preflight accuracy analysis studies can accurately predict the advantages of new data types.

VI. Venus Encounter to TCM 3

During the period between Venus encounter and TCM 3 (13 days before Mercury) the spacecraft experienced several episodes of moderate unmodelable accelerations. As shown in Fig. 8, the solutions based upon conventional data and the batch filter separated into three groups depending on whether state or state and stations were estimated and whether near-Venus data were or were not included. The scatter between these conventional data solutions was 250 km, which was 2-1/2 times the accuracy required by the mission. The sequential solutions using the conventional data were much less scattered (~75 km). The solutions based upon the differenced doppler also were much less scattered (50 km) and showed very little dependence on what parameters were estimated.

Also included in Fig. 8 is the current best estimate (CBE) of the premaneuver trajectory. Because of the pre-Mercury maneuver this CBE has an associated uncertainty of 50 km. From Fig. 8, it is clear once again that, in the presence of moderate unmodeled accelerations, the batch filter solutions using the differenced doppler data are nearly an order of magnitude superior to batch filter solutions using conventional data.

VII. TCM 3 to Mercury Encounter

TCM 3 occurred 13 days before Mercury encounter. During those 13 days only 9 passes with good overlapping data were taken. The simultaneous data were seriously degraded by an apparent 20-mHz jump in the frequency system of station 43. These data have been processed, however, since there are only a small amount of data and they are corrupted by the frequency jump; the results will not be shown here. In passing we will just mention that the orbit determination results agree with the CBE to within 50–100 km.

VIII. TCM 4 to TCM 5 (Superior Conjunction)

Between TCM 4 (May 9, 1974) and TCM 5 (July 2, 1974), the Sun-Earth-probe (SEP) angle remained under 7 deg and reached a minimum of about 1.7 deg at superior conjunction. The effect of the solar corona on the doppler data was very significant and generated data noise as high as 0.2 Hz (at 300-s count time). Because the ray paths of the signals from the spacecraft to widely separated tracking stations are very similar, the effect of the solar corona on the down-link two-way and three-way data should be nearly common. Thus it was hoped that differencing the two-way and three-way data should remove much of the noise induced by the solar corona. Figure 9 shows the two-way, three-way, and differenced data residuals from a pass of data taken four weeks before superior conjunction. It is clear from this figure that the effects on the two-way and three-way data are nearly common and the noise on the differenced data is 5–10 times smaller than the noise on the conventional two-way data. Figure 10 contains the per-pass standard deviations of both the 5-min conventional and differenced doppler data. Generally the differencing process reduces the noise by a factor of 5.

Unfortunately, the Australian stations were usually unavailable for tracking between the fourth and fifth maneuvers. The differenced doppler data during this period consisted of 1- to 3-h Spain-Goldstone tracking passes. Even with this limited amount of data, the long arc for the second Mercury encounter solutions using the differenced data agreed with the conventional long arc solutions to within a few hundred kilometers. Because of the large noise contained in the data around superior conjunction, the short arc (10 to 20 days) conventional data solutions (both batch and sequential) were generally quite unstable, having a scatter of approximately 2,000 km. However, the short arc differenced data solutions were much better having a scatter of about 500 km. This factor-of-four improvement in the orbit determination solutions brought about by the differencing process is very encouraging.

If the noise in the differenced doppler data can be attributed entirely to electrons in the solar corona, an estimate of the electron density gradient can be made. The ray paths that pass the Sun at 4.5 solar radii and continue to Goldstone and Madrid are separated by about 2,000 km when they pass the Sun. For this particular pass the average difference between the three-way and two-way doppler residuals was about 0.035 Hz. Therefore, the gradient of the electron density would be 0.035 Hz/2000 km = 0.017 Hz/1000 km = 1.1×10^{14} (electrons/m^2)/s/1000 km.

IX. Conclusions

The Mariner 10 differenced doppler (QVLBI) demonstration conclusively showed that this new data type can reduce the effects of moderate unmodeled spacecraft accelerations (10^{-10} km/s^2) by an order of magnitude and reduce the effects of the solar corona by a factor of five. The differenced data solutions were also very useful in making real-time navigation decisions for use by the Mariner 10 project. To demonstrate that the differenced data can be used to effectively remove the effects of small (10^{-12} km/s^2) unmodeled accelerations, it will probably be necessary to have full S-band–X-band (S/X) charged particle calibrations and either frequency systems based on hydrogen masers or SITT Data. Hopefully, such data will be available from the Viking spacecraft for the two months preceding the encounter with Mars.

Acknowledgment

The authors wish to thank S. J. Reinbold and R. E. Koch for their constant help in the data processing and making O. D. runs. Thanks are also due to K. W. Yip for his assistance during TCM 3 (Mercury delivery).

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Table 1. QVLBI doppler demonstrations

Phase	Spacecraft	Baseline	Frequency system	Purpose
1	Pioneers and Mariners	Short[a]	Rb[c]	Determine pertinent characteristics of Rb oscillator
2	Pioneer 10	Long[b]	Rb	Show that simultaneous doppler reduces effects of large unmodeled accelerations ($> 10^{-8}$ km/s^2) by two orders of magnitude
3	Mariner 10	Long	Rb	Show that simultaneous doppler reduces effects of moderate unmodeled accelerations ($10^{-10} \rightarrow 10^{-11}$ km/s^2) by an order of magnitude
4	Helios, Pioneer, Mariner, Viking	Short	H[d]	Determine pertinent characteristics of H-maser
5	Viking	Long	H	Show that simultaneous doppler reduces effects of small unmodeled accelerations (10^{-12} km/s^2) by order of magnitude

[a]Distance between tracking stations less than ~100 km.

[b]Distance between tracking stations greater than ~5000 km.

[c]Rb = rubidium.

[d]H = hydrogen.

Table 2. Estimated and considered parameters and their a priori values

Parameter	Estimated a priori	Considered a priori
X, Y, Z — S/C position	10^4 km	
$\dot{X}$, $\dot{Y}$, $\dot{Z}$ — S/C velocity	1 km/s	
A100 i (frequency offset)	1.0×10^{-10} (0.229 Hz)	14.42×10^{-12} (0.03 Hz)
A200 i (frequency drift)	1.0×10^{-16} (0.229 Hz/10^6 s	0.3×10^{-17} (0.0069 Hz/10^6 s)
r_s station location in cylindrical coordinates	3 m	3 m
L_o	0.54772×10^{-4} deg	0.54772×10^{-4} deg
z	15 m	15 m
GR, GX, GY — solar pressure coefficients		0.5 D-1
ATAR, ATAX, ATAY — nongravitational accelerations		1. D-11
MUF, MUP, MUB, NUF, NUP, NUB — solar pressure coefficients		1. D-2
Data weights		
Differenced doppler		0.007 Hz
Conventional 2-way doppler		0.7 Hz
Range		10 km

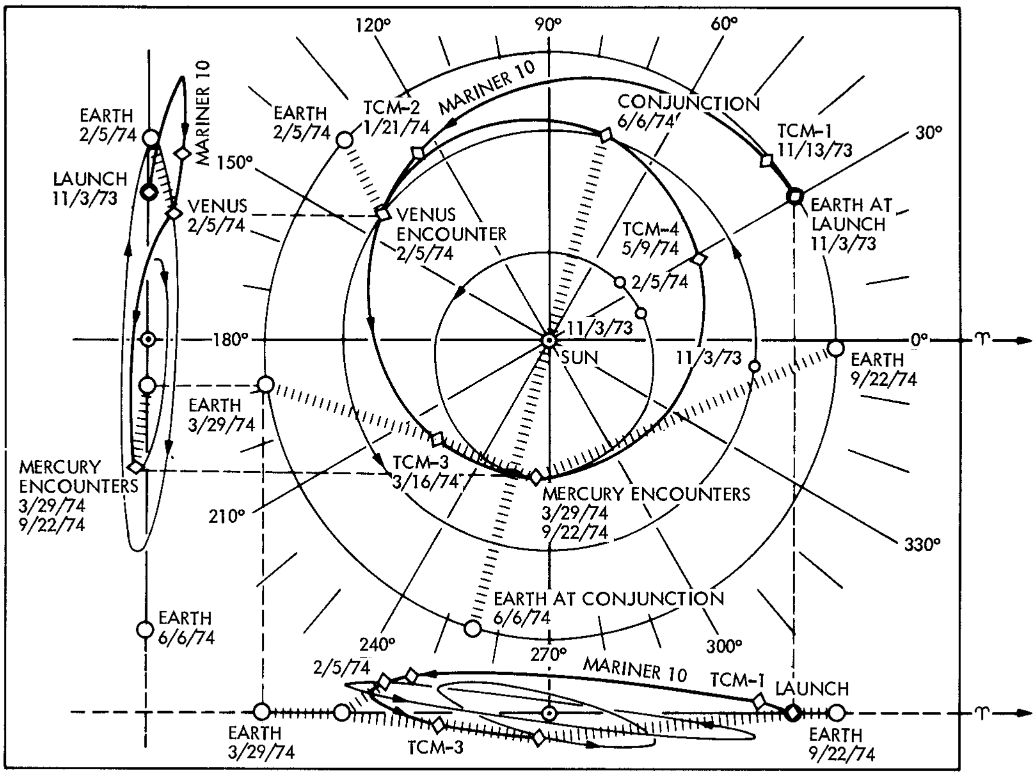

Fig. 1. Mariner 10 trajectory viewed from above and edge-on; relative inclinations are 3 deg for Venus and 7 deg for Mercury

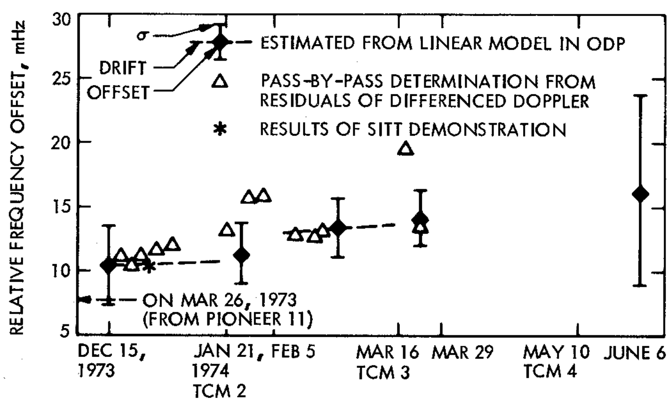

Fig. 2. Values of relative frequency offset of short baseline QVLBI demonstrations (DSSs 12 and 14)

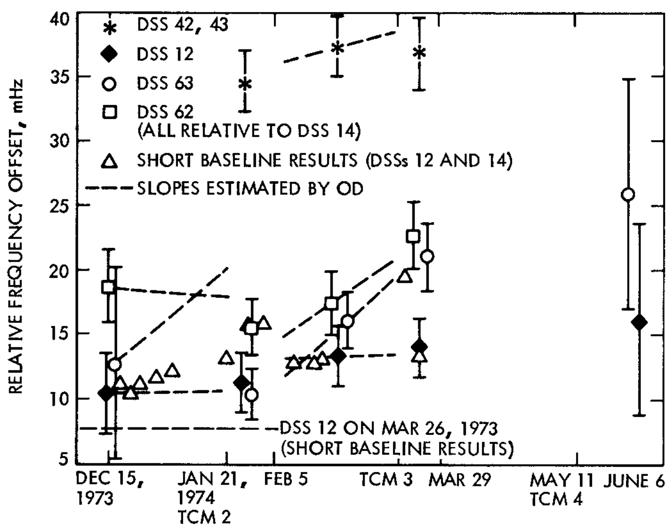

Fig. 3. Values of estimated frequency offset relative to DSS 14

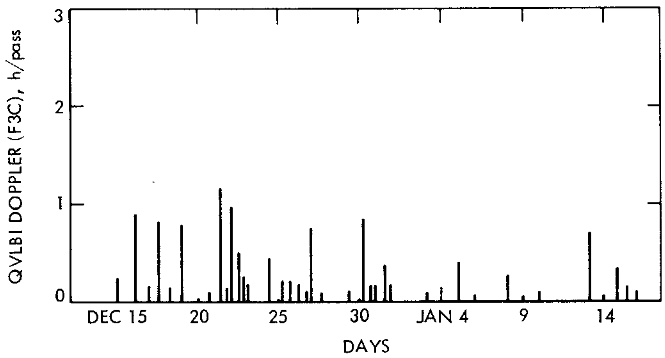

Fig. 4. Distribution of QVLBI doppler data (Dec 15 to TCM 2)

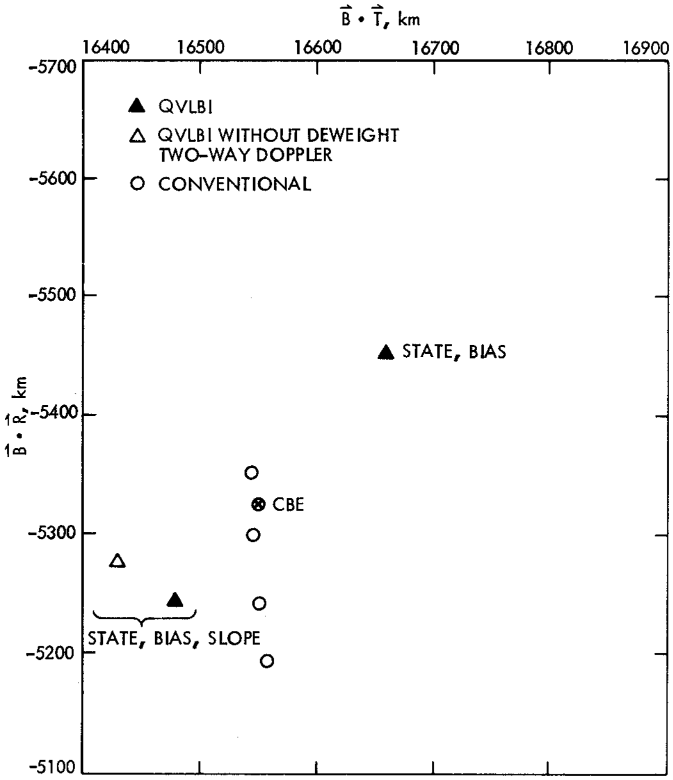

Fig. 5. Venus B-plane predictions pre-TCM 2

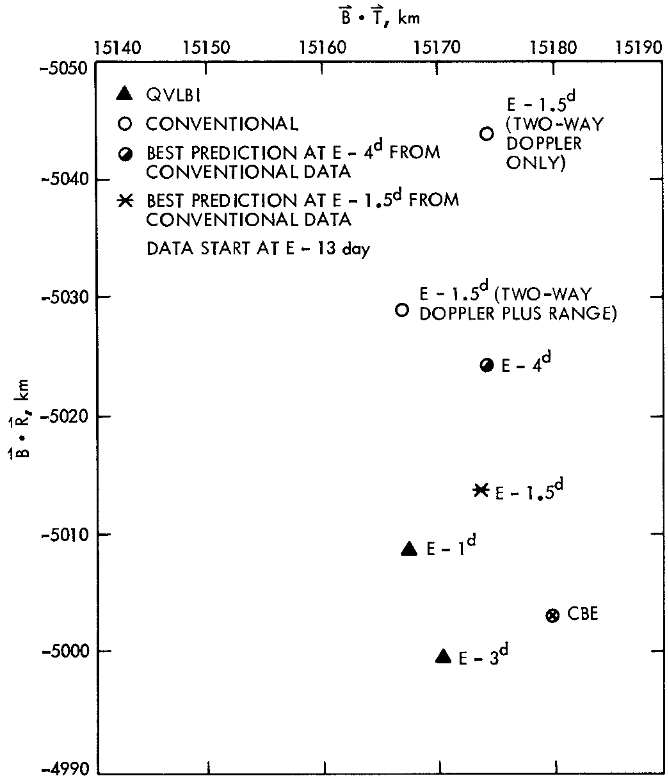

Fig. 6. B-plane predictions a few days before Venus encounter

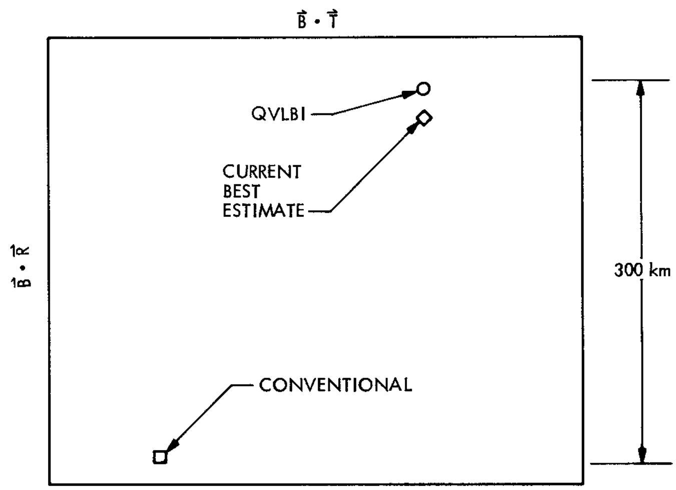

Fig. 7. Conventional and differenced data solutions using data from Venus −13 d to Venus −3 d with no solar pressure model

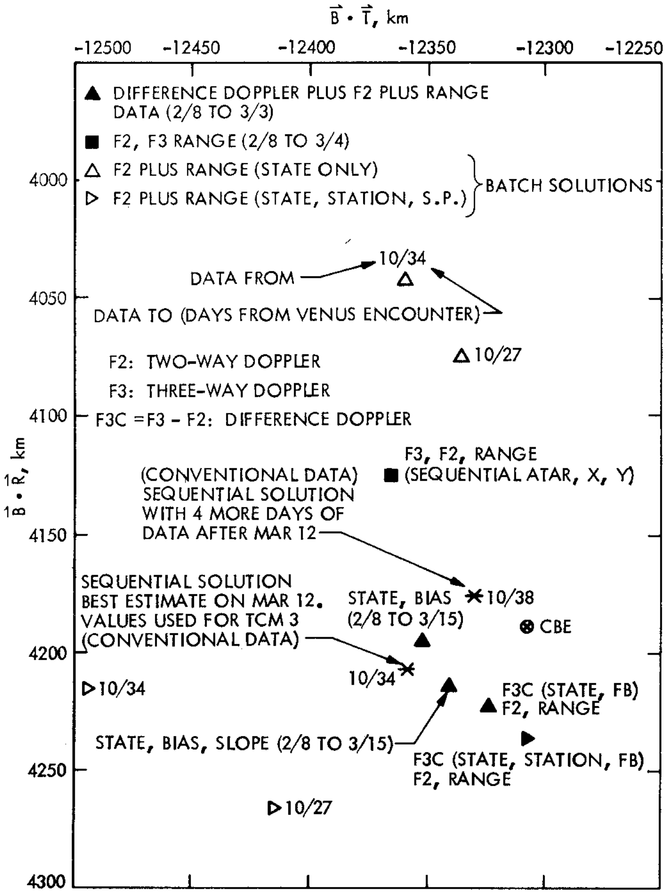

Fig. 8. Mercury B-plane predictions at TCM 3

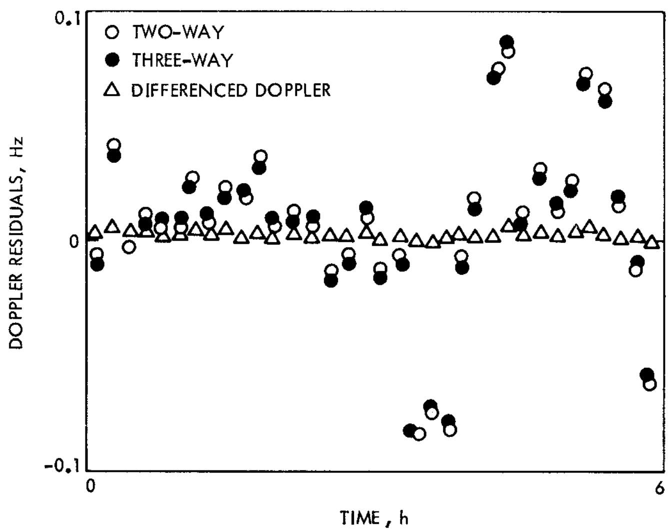

Fig. 9. Two-way, three-way, and differenced doppler four weeks before superior conjunction

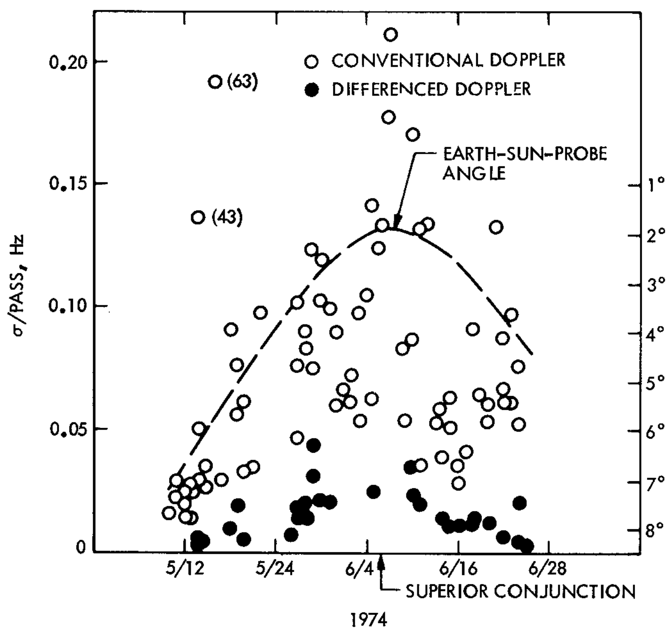

Fig. 10. Standard deviation per pass of two-way and differenced doppler residuals